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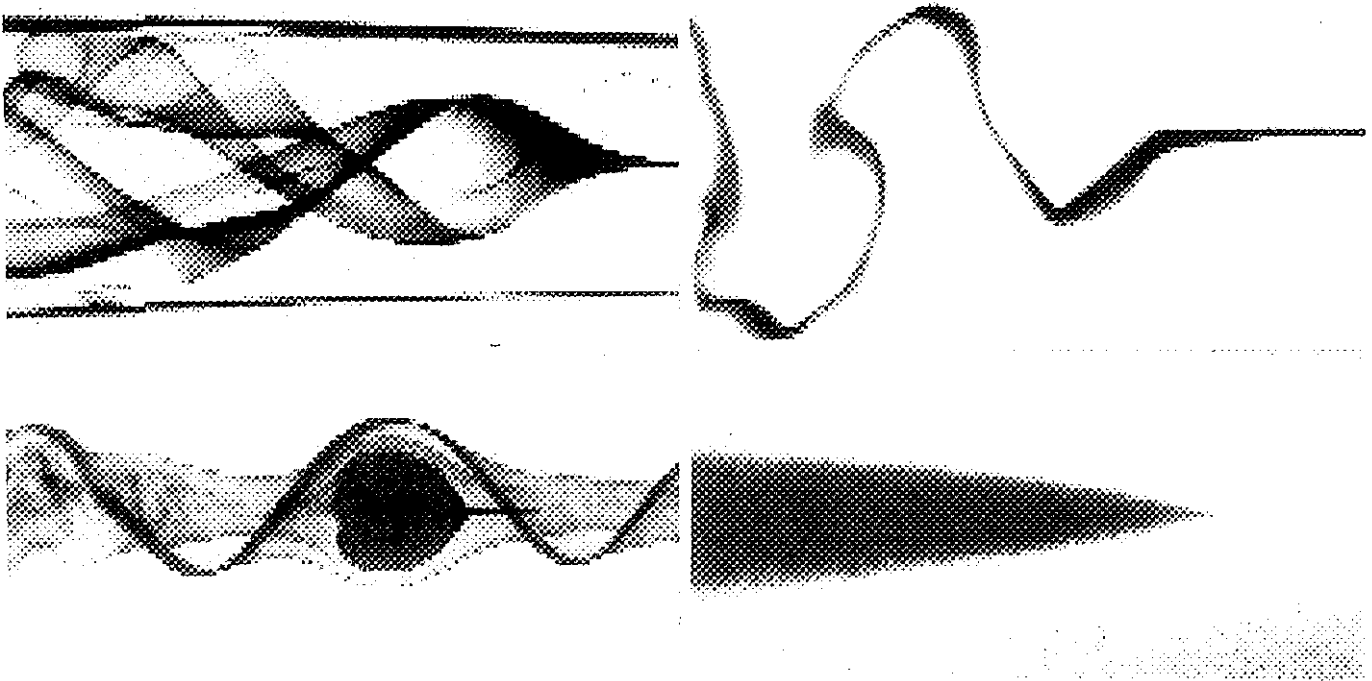


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VORTEX BREAKDOWN AND TURBULENCE

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Abstract

This paper describes experiments on various types of vortex breakdown in *non-cavitating* swirling flows in a slightly diverging cylindrical tube at Reynolds numbers up to $U_0 D_0 / \nu = 225,000$. In addition to the well-known double-helix, spiral, and nearly axisymmetric types, a fourth fundamental type of breakdown (the explosive formation of an almost axisymmetric conical turbulent wake) has been discovered. The evidence presented herein shows that the state of the ambient flow has a profound effect on the topology of the breakdown and that the new form is indeed the most robust of all the known breakdowns.

Nomenclature

D_b	diameter of the recirculation bubble
D_0	diameter of the test tube
L_b	length of bubble
Re	Reynolds number, $Re = U_0 D_0 / \nu$
t	time
U_0	cross-sectional averaged velocity
u'	axial velocity fluctuations
x	axial distance measured from the start of the diverging tube
x_s	axial distance measured from the stagnation point
Γ	circulation of the vortex
γ	half angle of divergence (1.432 deg.)
Ω	circulation number, $\Omega = \Gamma / U_0 D_0$
ν	kinematic viscosity of water

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Introduction and Brief Review

Vortices may experience breakdown (an impressive structural change) depending on the nature and nurture of their creation and evolution. The understanding of the consequences of the breakdown depends in part on the understanding of its topology and in part on a detailed map of its velocity, turbulence, and stress field, validated by experiments or numerical calculations. Since its discovery, many theoretical and experimental studies have been conducted. The difficulties experienced in describing the nature, identifying the occurrence, and predicting the characteristics of the breakdown in tubes, over delta wings, and in covered or topless cylindrical containers have been well documented.

This paper, which is the sequel to the author's three previous publications¹⁻³, first presents a brief summary of some of the important facts which have emerged from the experimental and numerical investigations of laminar vortex breakdowns and then describes the observations made in turbulent swirling flows with some surprising results. These may stimulate further interest in the numerical imitation of the three-dimensional turbulent vortex breakdown, thought to be of greater practical interest in hydro- and aerodynamics.

Working with swirling flows in tubes, Sarpkaya¹⁻³ has shown that:

(i) There is a third fundamental form of vortex breakdown (double helix), in addition to the other two previously known forms: spiral and nearly axisymmetric;

(ii) In tubes, the sense of rotation of the spiral is identical to that of the fluid surrounding the original filament;

(iii) The nearly-axisymmetric form, and for that matter all forms of vortex breakdown show oscillations of various amplitudes along the axis of the tube;

(iv) There is an inclined vortex ring (a toroidal vortex) near the downstream end of the recirculation "bubble" which gyrates at a regular frequency about the axis of the tube. Thus, not only externally but also internally, the bubble is not axisymmetric;

(v) The simultaneous filling and emptying of the "bubble" is controlled by the motion of the said vortex ring;

(vi) When the swirl is increased, the bubble first moves downstream (contrary to what is expected) and then moves rapidly upstream, overshooting its final steady-state. A rapid decrease of swirl results in similar motions in reverse order;

(vii) The "steady-state" diameter of the bubble is about 0.3 times that of the tube. The bubble diameter decreases (increases) when the bubble, in transient motion, moves upstream (downstream);

(viii) The length-to-diameter ratio, L_b/D_b of the steady-state bubble varies between 1.35 and 1.45. In transient states, an increase (decrease) in bubble diameter results in a corresponding decrease (increase) in bubble length;

(ix) Three or more bubble-like breakdowns can simultaneously exist along the tube in a transient state created by a proper management of the angular momentum imparted to the flow;

(x) The type and location of stationary breakdowns are functions of Reynolds ($Re = U_0 D_0 / \nu$) and circulation numbers ($\Omega = \Gamma / U_0 D_0$);

(xi) There is a vortex-breakdown hysteresis region where two stable breakdown conditions exist. Many intermediate forms of breakdown occur between the nearly-axisymmetric and spiral types, depending on the rate of change of Reynolds and/or circulation numbers. Using an identical experimental apparatus (constructed from measurements and photographs provided to S. Leibovich by this writer), Faler and Leibovich⁴ also observed the same flow states, as expected, but preferred to classify them into six different types.

Such classifications are somewhat arbitrary and does not enhance one's understanding of the physics of the transient phenomenon;

(xii) The nearly-axisymmetric form evolves either from a double helix, or from a spiral, or directly from a local axisymmetric swelling of the vortex core. The mode of evolution depends on the conditions surrounding the nature and nurture of the breakdown: circulation number, Reynolds number, velocity profiles, turbulence of the ambient flow, the geometry of the body in or above which the breakdown takes place (vane and tube apparatus, delta wing, rotating tops or bottoms, with or without side walls), just to name a few of the governing parameters;

(xiii) The swirl angle distribution depends on the breakdown form. For a bubble shape, it is about 55° ;

(xiv) The adverse pressure gradient has a profound effect on the occurrence and position of vortex breakdowns. An increase in adverse pressure gradient has the same effect on breakdown position as an increase in circulation or the mean-flow rate—that of shifting the breakdown location upstream—as long as the boundary layer on the tube wall does not separate. The nonlinear interaction between the adverse pressure gradient, separation of the swirling flow, and the vortex breakdown is considerably more complex particularly when the basic flow is *turbulent*, and finally,

(xv) It was also stated twenty years ago by Sarpkaya³ that "it does not appear that under the circumstances described herein recourse can be made to the full equations of motion for the prediction of the *turbulent* breakdown characteristics."

Most of the foregoing facts have been confirmed both experimentally (see, e.g., Brücker and Althaus⁵; Althaus, Brücker, and Weimer⁶) and numerically (see, e.g., Spall and Gatski⁷, Dély⁸, Visbal⁹) for laminar flows. Some of the facts, such as the non-existence of axisymmetry, the importance of the adverse pressure gradient, and the transient behavior of the breakdown (upstream, downstream excursions of the bubble) have been independently rediscovered a number of times.

The additional facts which have emerged during the past twenty years are:

(i) The phenomenological explanations of the breakdown (the quasi-cylindrical approach and analogy to boundary-layer separation, the concept of critical state, hydrodynamic instabilities, weakly non-linear and non-axisymmetric waves on an incompressible vortex, and bifurcation theory in search of multiple axially symmetric steady solutions) fell short of providing satisfactory explanations (see, e.g., Détery⁸ for a detailed discussion of these);

(ii) Even the simulation of laminar breakdown requires the use of the 3-D, unsteady, Navier-Stokes equations. The initial, inflow, and boundary conditions are difficult to prescribe and there are as many different upstream velocity profiles as there are experimental conditions. In fact, the behavior of the breakdown is as much sensitive to boundary conditions as it is to the adverse pressure gradient;

(iii) The growth of the negative azimuthal vorticity is necessary in order to eventually stagnate the vortex core (Brown and Lopez¹⁰, Darmofal¹¹). The increasing asymmetry of the circumferential vorticity distribution, the disruption of the outer flow, the subsequent deflection of the stagnation point away from the vortex axis, and the intensification of the core deceleration due to the stretching of the azimuthal vorticity precede the inception of breakdown;

(iv) The search for simple universal numerical criterion is not in keeping with the strong dependence of the breakdown on upstream, downstream, and in-between conditions. Only case-specific criterion may be developed within a narrow range of steady-flow conditions. The eventual understanding of the breakdown as to why does it occur, where does it occur, and what happens when it occurs requires the distribution of the complete velocity and turbulence profiles far upstream of the breakdown;

(v) Contrary to some assertions that "in many circumstances turbulence does not play an essential role in the breakdown itself" (Détery⁸), turbulence does indeed play an important role in the breakdown of high-speed swirling flows, particularly those involving practical applications;

(vi) The direct numerical simulation (DNS) of breakdown at relatively small Reynolds numbers

is not yet in a position to shed light on the behavior of turbulent vortex breakdown;

(vii) The transient excursions of the breakdown also occur in leading edge vortices over delta wings. The sense of rotation of the spiral breakdown is, however, in the opposite direction to that of the basic flow, unlike that in tubes. Otherwise, the quasi-steady and transient behavior of laminar breakdown over stationary or pitching model delta wings at relatively low Reynolds numbers are not fundamentally different from those observed by Sarpkaya¹ in diverging tubes over twenty years ago.

Visbal⁹ performed numerical simulations of the onset of vortex breakdown above a pitching delta wing, using the full unsteady, three-dimensional Navier-Stokes equations, at a chord Reynolds number of 9.2×10^3 and concluded that the predictions agree with similar experiments, the angular delay and onset of breakdown are strongly linked to the pressure gradient prevailing along the vortex axis, and the upstream-migrating bubble becomes increasingly asymmetric and open ended, as expected. On the basis of the resemblance of the computed isosurface of constant total pressure with experimental flow visualization of laminar "axisymmetric" breakdown in a tube, Visbal⁹ concluded that "vortex bursting over a delta wing at a high angle of attack is more closely related to vortex breakdown in a tube than previously shown." The present study shows that this conclusion is true only if both flows are laminar or both flows are turbulent, and not otherwise. Clearly, the most important advantage of the numerical simulations of laminar swirling flows is that they yield contours of the quantities, such as velocity, vorticity, and pressure, which are rather difficult to measure in a bubble either undergoing small amplitude oscillations in a steady ambient flow or large excursions in response to an externally-imposed unsteadiness.

Ekaterinaris and Schiff¹² used the thin-layer Navier-Stokes equations to investigate the swirling flow over a 75° sweep ($AR = 1.07$) delta wing at a Mach number of $M = 0.3$ and Reynolds number (based on the wing-root chord) $Re_c = 0.9 \times 10^6$. Initially, the flow was assumed to remain laminar. Subsequently, the effect of turbulence modeling on the computed flow was investigated using the Baldwin-Lomax algebraic eddy-viscosity model with some modifications to account for crossflow separation.

Their computed flow-field of the vortex breakdown is not sufficiently detailed to allow a direct comparison with experiments. However, they have noted that the core of the vortex expands and the flow is diverted downstream of the vortex burst point, i.e., the breakdown bubble remains open in the wake region in both laminar and turbulent flows. The fact that the downstream end of the bubble is always open for simultaneous filling and emptying has been known for a long time (Sarpkaya¹). However, the fact that the topology of the breakdown and the degree of opening of the downstream end of the bubble depend on turbulence has not yet been enunciated by any investigator. Délerly and Molton¹³ examined the topology of the flow resulting from the breakdown over a delta wing at a chord-based Reynolds number of $Re = 1.46 \times 10^6$. Presumably, the ambient flow was laminar since the word turbulence was mentioned only once in connection with the "spectacular amplification of the turbulence level in the dilatation of the vortex." They were primarily concerned with the force fields and the effect of the breakdown on the flow structure in the immediate vicinity of the wing surface rather than with the details of the breakdown structure. Nevertheless, they have concluded, on the basis of their velocity measurements, that the reversed flow region is relatively small and rapidly contracts and disappears and the streamwise mean velocity becomes everywhere positive again at a short distance from the breakdown point. However, their use of the mean velocity components across an oscillating breakdown bubble to draw conclusions about the structure of the breakdown may be questioned.

Spall and Gatski¹⁴ have recently used the three-dimensional, unsteady, incompressible, Reynolds-averaged Navier-Stokes equations in conjunction with two different turbulence models (standard $K - \epsilon$ and an explicit, regularized algebraic Reynolds stress model), in a study unimpeded by competing and complicating influences such as combustion or complex body motions, to predict the characteristics of the bubble-type vortex breakdown at a Reynolds number of 10^4 (based on vortex core radius). Among other things, they have predicted that the algebraic Reynolds-stress-model produces a breakdown bubble with a larger length-to-diameter ratio than does the $K - \epsilon$ model, both models yield a single nearly axisymmetric toroidal recirculation region, rather than a multi-celled structure as in laminar bubbles

and, compared to the laminar cases, the overall size of the turbulent bubble is *larger* (see Figs. 1a through 1c). The flow structure in Figs. 1a and 1b is not calculated beyond $x/\sigma = 40$. Even though, Fig. 1c suggests the formation of a spiral breakdown beyond $x/\sigma \approx 25$, Figs. 1a and 1b do not provoke such a suggestion. This is further supported by the vorticity contours provided by Spall and Gatski¹⁴ which show that the average vorticity in the turbulent wake is about one half of that in the laminar wake, suggesting that the formation of a spiral breakdown is rather unlikely.

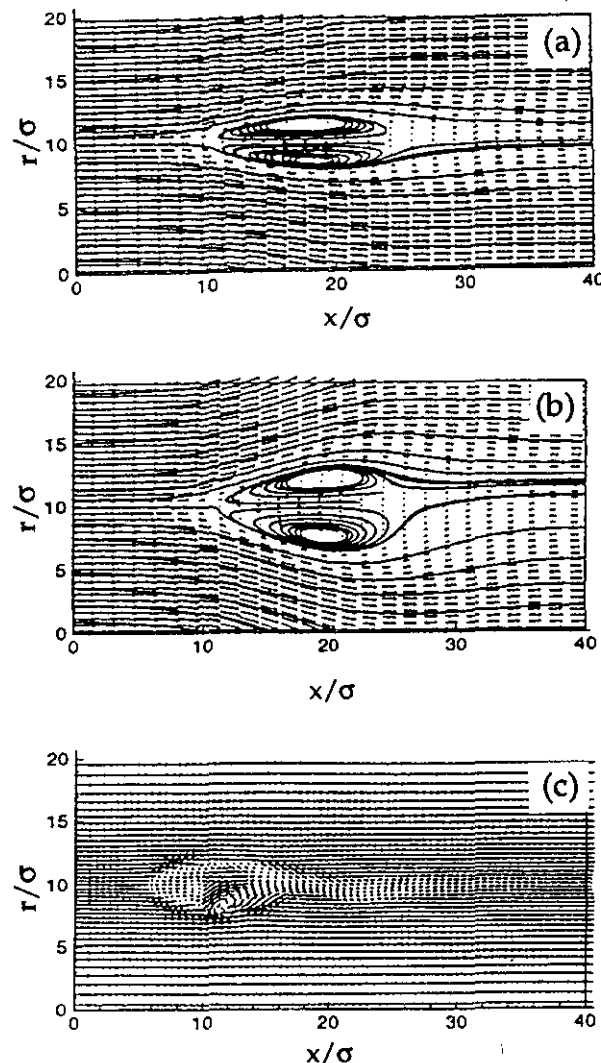


Fig. 1 Streamlines and velocity vectors for vortex breakdown (along vortex centerline).

(a) Algebraic Reynolds stress model,

$Re = U_0\sigma/\nu = 10,000$;

(b) $K - \epsilon$ model, $Re = U_0\sigma/\nu = 10,000$;

(c) Laminar breakdown, $Re = U_0\sigma/\nu = 200$.

(From Spall and Gatski¹⁴)

Even though the literature is abound with numerical and experimental studies of swirling turbulent flows (see, e.g., Rhode et al.¹⁵), most works are dedicated either to the development of simple criteria for the identification or position of the vortex breakdown over delta wings or to the improvement of the efficiency of combustion. Often the circulation imparted to the flow in a particular combustion-chamber is such that the breakdown reaches the upstream end of the combustion chamber. None of these studies attempted to delineate the topology of the vortex breakdown, an ingredient necessary to the enhancement or to the alleviation of the consequences of vortex breakdown. The effect of turbulence and swirl became inextricably involved with the fact that combustion alone leads to adverse pressure gradient, and possibly to vortex breakdown. Clearly, what is needed is a relatively simple experiment, without competing influences, to assess the effect of turbulence on vortex breakdown. It is against this background that the observations made over the past three years of the topology of vortex breakdown in swirling turbulent flow (in almost exactly the same flow apparatus that was previously used by Sarpkaya¹) will be described in some detail.

Experimental Apparatus and Procedure

The original experimental equipment (see Fig. 2) consisted of a Plexiglas water tank, adjustable swirl vanes, a diverging pipe, a constant head reservoir, a rotameter, and the necessary piping system. Its characteristics have been described in some detail in Sarpkaya¹. Here only the modifications made to it for its adaptation to the present investigation are presented. The small constant head tank was replaced by a 5 Hp pump which circulated the water between the apparatus and a large reservoir. There was no cavitation anywhere in the test tube in any of the high-Reynolds-number experiments reported herein.

In one series of experiments, tripping wires were attached to one or both sides of the converging flow (see Fig. 2). The results were not significantly different from those reported herein (without the use of tripping wires). The small differences resulted from the occurrence of particular forms of breakdown at slightly smaller Reynolds numbers. Otherwise, no changes were made on the original apparatus shown in Fig. 2 in order to be able to state unambiguously that the laminar and turbulent non-

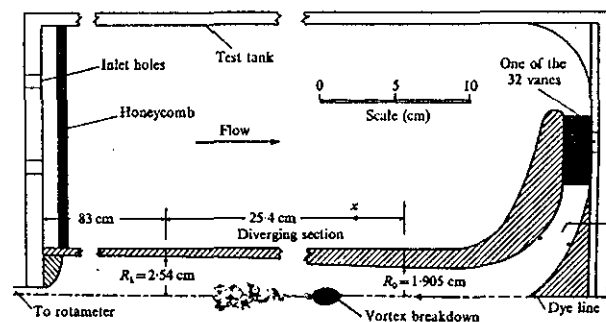


Fig. 2 Top half of the experimental apparatus

cavitating flow experiments were conducted in the same apparatus in the nominal range of Reynolds numbers from about $Re = 1000$ to $Re = 225,000$. A regular video system and food coloring, as before, were used to record the flow features. A 2-D LDV system (TSI) was used to make selected turbulence measurements at the edge of the vortex core ($x/\sigma = 1$) at $x/R_0 = 1$ and in the expanding wake, downstream of the breakdown, in order to get some information about the turbulence levels. Large number of data points (2024) were collected for each velocity component at each point of measurement. The sampling rate was well above the integral time scale of the flow. The flow was seeded with 6-12 μm particles of specific gravity of 1.2. A detailed mapping of the velocity and turbulence distributions will be presented in the near future through the use of a 3-D (Dantec) LDV system, acquired recently.

The position of the breakdown, relative to the point where the divergence of the tube started, could be varied either by setting the vane angle at a desired value and then changing the flow rate at suitable intervals (constant Ω), or by maintaining the flow rate at a desired value (constant Re) and then systematically altering (increasing or decreasing) the vane settings (variable Ω). In the current experiments, primarily the former method was used for two reasons. Even though both methods eventually lead to similar results for "stationary breakdowns, it is easier to change the Reynolds number in small increments because the position of the vortex breakdown at high Reynolds numbers is rather sensitive to small changes in Ω . Thus, it is advantageous to increase the Reynolds number near the desired value and then make small adjustments on Ω in order to bring the breakdown to the desired x/R_0 position (about 5 in most of the current experiments). Note that increasing Re , while maintaining Ω constant, decreases the core size and

increases both the vorticity and the axial velocity in the core.

Observations and Discussion of Results

The first series of experiments were a careful repeat of those reported earlier by Sarpkaya¹ in the range of $1.2 < \Omega < 3.0$ and $4.6 \times 10^2 < Re < 1.1 \times 10^4$. All of the major findings summarized earlier as well as the vortex-breakdown position x/R_0 versus Re in terms of Ω , the swirl angle versus radial distance r/R_0 , and the velocity of the vortex-core filament in terms of the relative distance from the breakdown position were confirmed.

The remainder of the investigation was devoted to the determination of the effect of turbulence on vortex breakdown at ever increasing Reynolds numbers in a cavitation-free environment.

The description to follow is based on extensive video viewing and the information extracted from it in terms of the occurrence of various types of

structures, mindful of the fact that the vagaries of flow visualization do not always provide correct insight into the physics of the actual occurrences. Furthermore, one can only repeat the complaint registered by practically all experimenters on this subject that still photographs (taken directly from the video screen using conventional photography or a videographic copier) do not convey as much information as motion pictures.

When Ω was set at approximately 0.77 and the Reynolds number was increased to about 5×10^4 , the breakdown moved upstream to about $x/R_0 \approx 5$ and remained there nearly stationary. The rms value of the streamwise component of turbulence at $r/\sigma = 1$ and $x/R_0 = 1$, normalized by the axial mean velocity at $x/R_0 = 0$, was 2.3%. As noted earlier, breakdowns do not normally remain stationary regardless of the quality of the control of the flow and angular momentum. They dart back and forth, with amplitudes dependent on the facility and other controlling parameters. Figure 3a shows the resulting breakdown. Figure 3b is a close-up view of Fig. 3a. They differ from the bubble-type

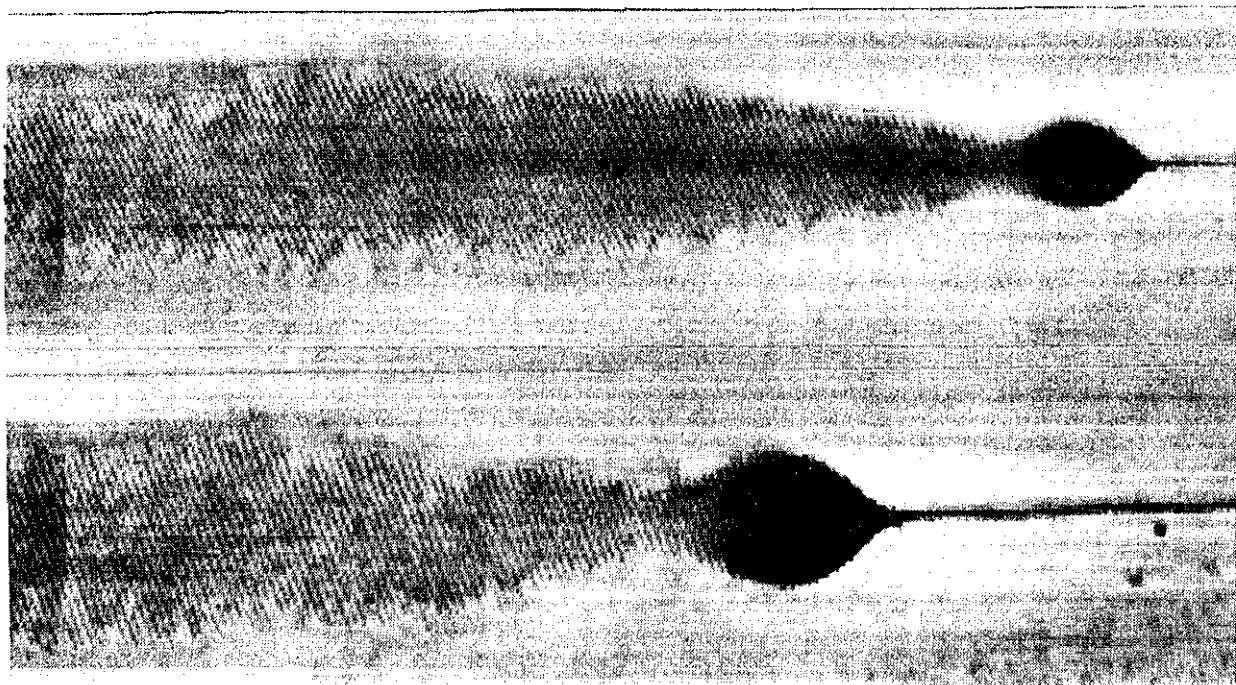


Fig. 3 "Bubble" type vortex breakdown.
(a) for $Re \approx 50,000$ and $\Omega \approx 0.77$; (b) a close-up view of (a).

breakdowns observed at much lower Reynolds numbers at $x/R_0 = 5$ in several ways (see Fig. 4 for $Re = 4.5 \times 10^3$ and $\Omega = 1.5$). The bubble in Fig. 3a is relatively more axisymmetric, its wake is like the tail of a comet and does not appear to contain any spiral-type breakdown, and the core-reconstitution region immediately downstream of the bubble (normally about one bubble length, see Fig. 4), is now considerably shorter, the opening at the downstream end of the bubble is somewhat larger (see the close-up view in Fig. 3b), and finally, the diameter of the new bubble ($0.09D_0$) is considerably smaller than that of similar bubbles ($0.3D_0$, see Sarpkaya¹) at the same x/R_0 . The rms value of the turbulence on the axis of the turbulent wake (at a point approximately $x_s / R_0 = 1$ where x_s is measured from the stagnation point) was about 6%.

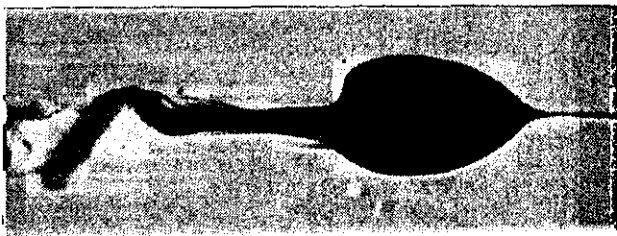


Fig. 4 Representative bubble type laminar vortex breakdown.

The differences between the high-Re and low-Re (say, $Re = 10,000$) became increasingly more accentuated as the Reynolds number was further increased, with required decreases in Ω so as to maintain the front stagnation point at $x/R_0 \approx 5$.

It is nearly impossible to cover the entire range of Reynolds numbers from about 50,000 to 225,000 at regular intervals to give a kaleidoscopic picture of the evolution of the breakdown topology. Instead, we will offer some mileposts. Figure 5 ($Re \approx 100,000$, $\Omega \approx 0.61$, rms value of $u'/U_0 = 4.7\%$ at $r/\sigma = x/R_0 = 1$ and about 9% on the axis of the turbulent wake at $x_s / R_0 = 1$) shows that the entire breakdown resembles a cone, growing almost linearly with distance downstream from a virtual origin. A small bubble-like structure may be seen in the immediate vicinity of the stagnation point. It is almost an integral part of the wake and its downstream end joins the rest of the wake in a very short distance. When the Reynolds number is further increased ($Re \approx 150,000$, $\Omega \approx 0.55$, rms value of $u'/U_0 = 8.4\%$ at $r/\sigma = x/R_0 = 1$ and about 13% on the axis of the turbulent wake at $x_s / R_0 = 1$), the bubble and the wake unite and become more like a turbulent cone, except very near the stagnation point where the rate of the radial expansion of the core is faster than the subsequent linear growth of the wake. It should be noted in passing that the wake further downstream does not rapidly fill up the entire cross-section of the test pipe. Instead, it grows as shown in Fig. 6 and resembles more and more a ballistic missile. When the Reynolds number is increased even further ($Re \approx 200,000$, $\Omega \approx 0.50$, rms value of $u'/U_0 = 11\%$ at $r/\sigma = x/R_0 = 1$ and about 17% on the axis of the turbulent wake at $x_s / R_0 = 1$), the "bubble" nearly disappears. The stagnation point is followed by a fairly sharp cone of turbulent flow as shown in Figs. 7a and 7b. Figure 7b shows the instant immediately after the dye supply is interrupted. The vortex core is barely visible because of the rapid diffusion of the remaining

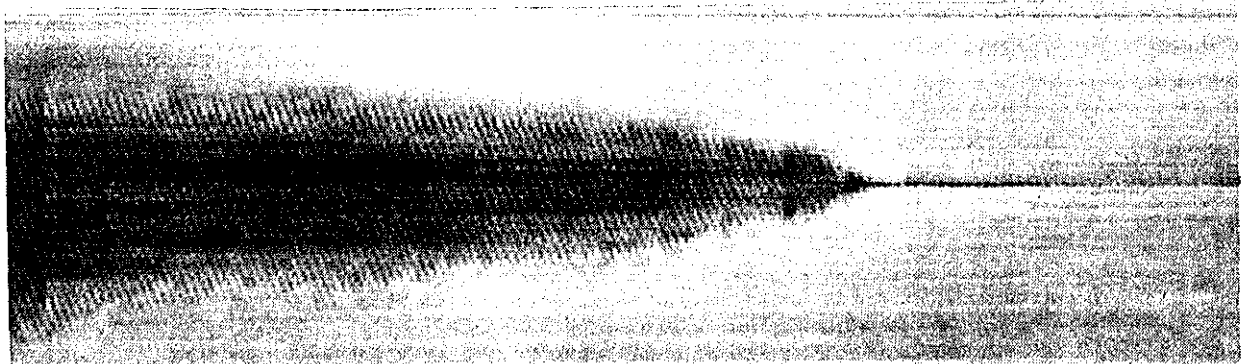


Fig. 5 Emergence of a conical vortex breakdown. Note that the "bubble" and the wake have almost completely merged ($Re \approx 100,000$ and $\Omega \approx 0.61$).

Fig. 7 The linear growth of the wake and the disappearance of the bubble ($Re \approx 200,000$ and $\Omega \approx 0.50$): (a) and (b) are before and shortly after the dye is interrupted.

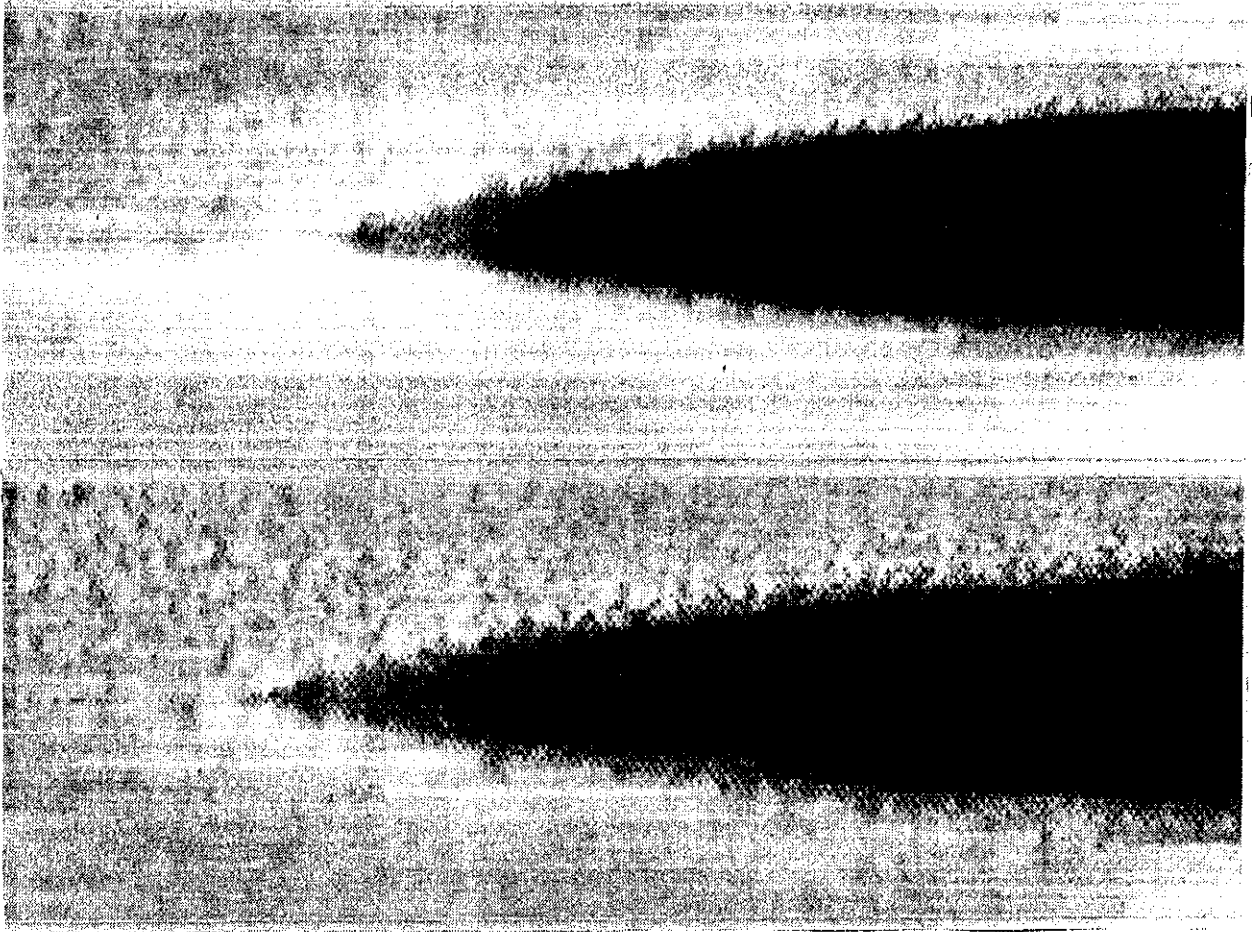
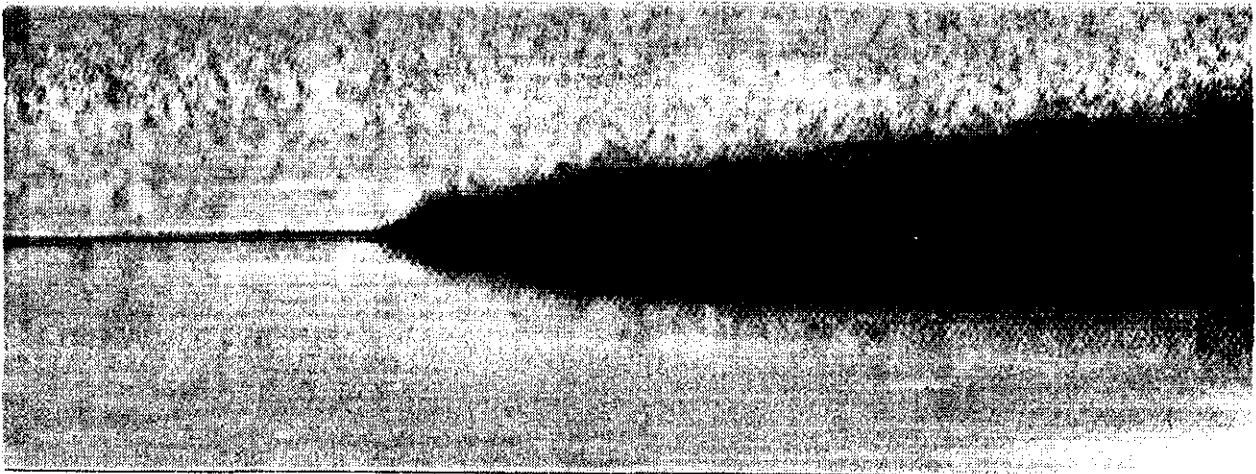


Fig. 6 Further development of a conical vortex breakdown ($Re \approx 150,000$ and $\Omega \approx 0.55$).



dye and the front of the cone is beginning to clear. The purpose of this figure is to expose the region in the immediate vicinity of the stagnation point. Relative to the previous cases, the cone is even sharper and everything in the cone is now fully turbulent flow (as far as one can tell from extensive observations and selective measurements). The existence of a "bubble" cannot be ascertained and there is no spiral breakdown. There is simply a stagnation point followed by a turbulent cone. Measurements behind the stagnation point to uncover a region in which there might be a recirculation region are nearly hopeless by any available means because of the high-frequency fluctuations of the stagnation point.

At higher Reynolds numbers ($Re \approx 225,000$, $\Omega \approx 0.46$) there were no additional changes. It appeared that the swirling flow has gradually arrived at a new form. We will consider this the fourth fundamental type of vortex breakdown (the conical type), in addition to the double-helix, spiral, and nearly axisymmetric types. It seems that of all the types, the axisymmetric form of the breakdown (the explosive formation of a cone-like turbulent wake) is indeed the most robust of all breakdown forms. Figure 8 shows, in full color, additional photographs of all fundamental forms of vortex breakdowns, from double helix to conical type.

A comparison of Figs. 1a and 1b (Spall and Gatsky¹⁴) with the results presented herein shows that there are fundamental differences between the observations and numerical predictions based on two different turbulence models. It may only be conjectured that the differences may be primarily due to upstream boundary conditions and, to a lesser extent, to the downstream boundary conditions. The development of the turbulent swirling flow in a pipe, rather than under the outer flow conditions prescribed by the numerical analysis, is not expected to account for the obvious differences since the laminar flow predictions of Spall and Gatsky⁷ compared very favorably with those observed by Sarpkaya¹.

Conclusions

The evolution of vortex breakdown in a swirling turbulent swirling flow at high Reynolds numbers led to the discovery of a fourth fundamental type of breakdown, called the conical type. The results refute the conjectures that the

circumstances of breakdown are insensitive to the Reynolds number and the local turbulence properties. These two factors have a strong influence not only on the development of the swirling flow prior to its breakdown but also on its topology after the onset of breakdown. At high flow rates, the disturbances and shear layers introduced by the vanes plus the development of turbulent boundary layers, (with or without tripping wires) along the side walls and the center body, in a rapidly accelerating flow lead, near $x/R_0 = 5$, to a highly complex non-equilibrium turbulence even if the flow were not swirling. If there is any hope of making realistic predictions of turbulent vortex breakdowns, the boundary conditions, in particular the velocity and turbulence profiles upstream of the breakdown, need to be known with great precision. Furthermore, if vortex breakdown is to be used to exploit its advantages, as in combustion, or to be avoided to escape its disadvantages, as in the case of delta wings, the experiments must quantify the conditions far upstream of the breakdown and the numerical calculations must adopt them as initial conditions. It is only then that it will be possible to assess the effect of often unknown and unknowable upstream disturbances on the behavior of vortex breakdown. We do not claim to have understood the consequences of turbulence on vortex breakdown, but we do claim that anybody conducting similar experiments in swirling turbulent flows in tubes at relatively high Reynolds numbers shall invariably arrive at the conical type of breakdown we have described herein.

Acknowledgments

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References

1. Sarpkaya, T., "On Stationary and Travelling Vortex Breakdowns," *Journal of Fluid Mechanics*, Vol. 45, Pt 3, Feb. 1971, pp. 545-568.
2. Sarpkaya, T., "Vortex Breakdown in Swirling Conical Flows," *AIAA Journal*, Vol. 9, Sept. 1971, pp. 1792-1799.
3. Sarpkaya, T., "Effect of Adverse Pressure Gradient on Vortex Breakdown," *AIAA Journal*, Vol. 12, No. 5, May 1974, 602-607.
4. Faler, J. H., and Leibovich, S., "An Experimental Map of the Internal Structure of Vortex Breakdown," *Journal of Fluid Mechanics*, Vol. 86, 1978, pp. 313-335.
5. Brücker, C., and Althaus, W., "Study of Vortex Breakdown by Particle Tracking Velocimetry (PTV): Part 1: Bubble-Type Vortex Breakdown," *Experiments in Fluids*, Vol. 13, 1992, pp. 339-349.
6. Althaus, W., Brücker, C., and Weimer, M., "Breakdown of Slender Vortices," Chapter 9 in *Fluid Vortices* (ed. S. Green), Kluwer Academic Pub., Norwell, MA (in press).
7. Spall, R. E., and Gatski, T. B., "A Computational Study of the Topology of Vortex Breakdown," *Proceedings of the Royal Society of London A*, Vol. 435, 1991, pp. 321-337.
8. Délery, J. M., "Aspects of Vortex Breakdown," *Progress in Aerospace Sciences*, Vol. 30, 1994, pp. 1-59.
9. Visbal, M. R., "Onset of Vortex Breakdown above a Pitching Delta Wing," *AIAA Journal*, Vol. 32, No. 8, pp. 1568-1575.
10. Brown, G. L., and Lopez, J. M., "Axisymmetric Vortex Breakdown: Part 2. Physical Mechanisms," *Journal of Fluid Mechanics*, Vol. 221, 1990, pp. 553-576.
11. Darmofal, D. L., "The Role of Vorticity Dynamics in Vortex Breakdown," *AIAA 93-3036*, *AIAA 24th Fluid Dynamics Conference*, 1993.
12. Ekaterinaris, J. A., and Schiff, L. B., "Numerical Simulation of Incidence and Sweep Effects on Delta Wing Vortex Breakdown," *AIAA J.*, Vol. 31, No. 5, 1994, pp. 1043-1049.
13. Délery, J., and Molton, P., "Topology of the Flow Resulting from Vortex Breakdown over a Delta Wing at Subsonic Speed," *Acta Mechanica [Suppl]*, Vol. 4, pp. 297-304.
14. Spall, R. E., and Gatski, T. B., "Numerical Calculations of Three-Dimensional Turbulent Vortex Breakdown," *International Journal for Numerical Methods in Fluids*, 1995 (in print).
15. Rhode, D. L., Lilley, D. G., and McLaughlin, D. K., "On the Prediction of Swirling Flowfields Found in Axisymmetric Combustor Geometries," *Journal of Fluids Engineering*, Vol. 104, 1982, pp. 378-384.

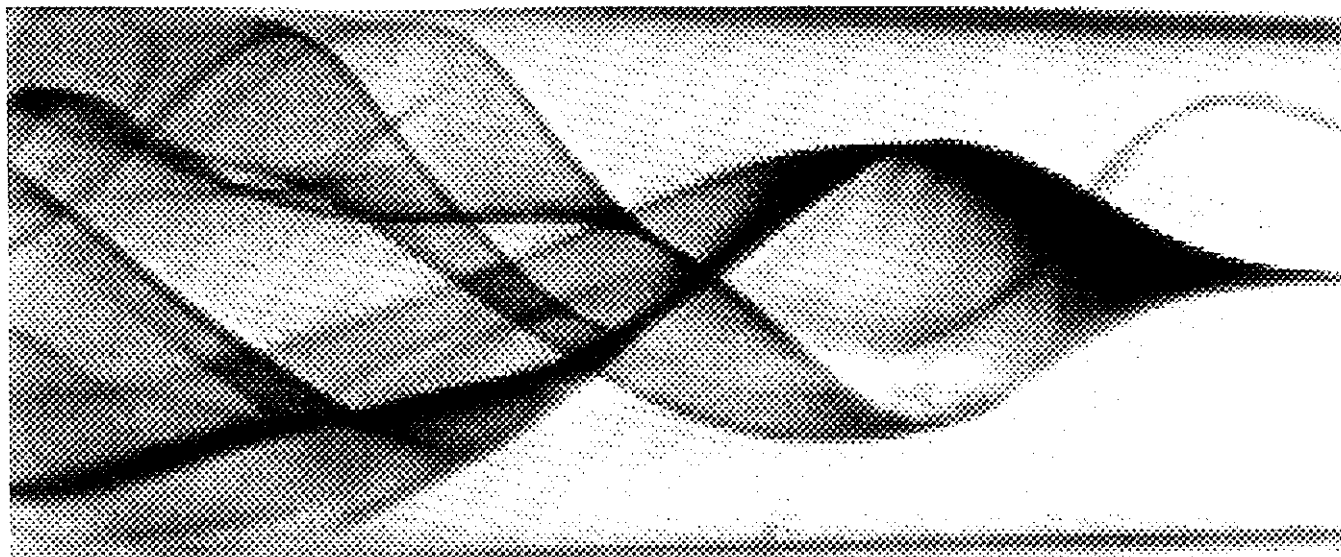


Fig. 8a Double-helix



Fig. 8b Spiral type of vortex breakdown

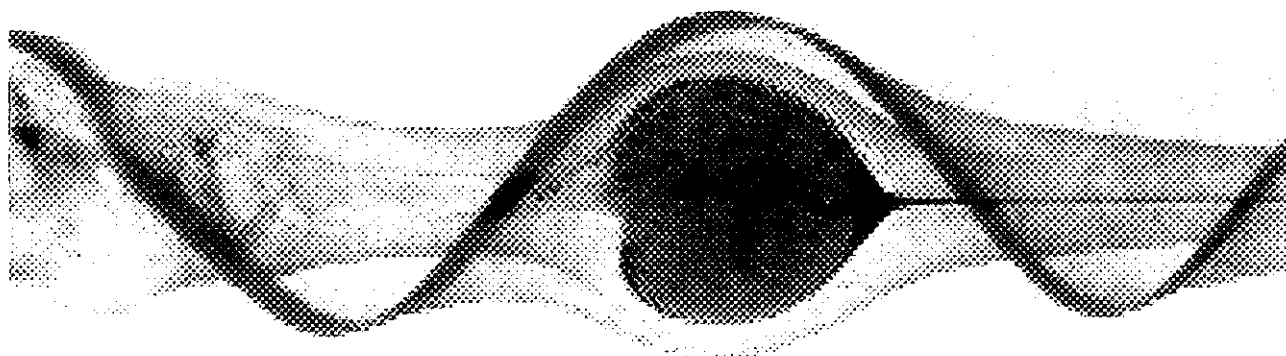


Fig. 8c Nearly-axisymmetric vortex breakdown

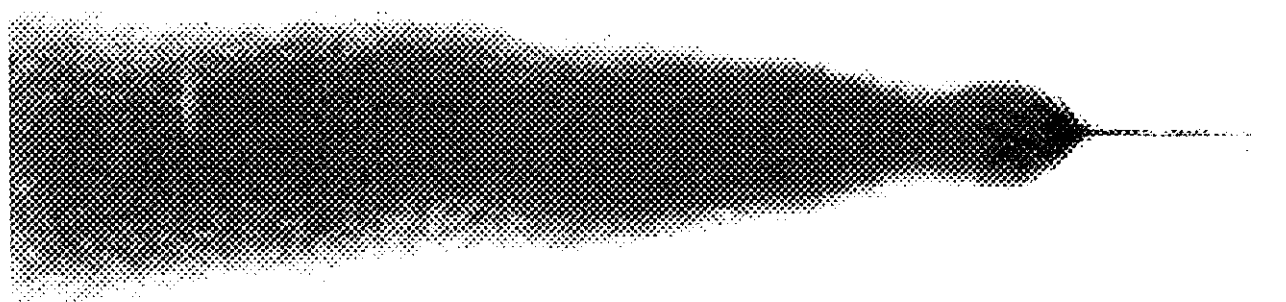


Fig. 8d Nearly-conical vortex breakdown for $Re \approx 50,000$ and $\Omega \approx 0.77$

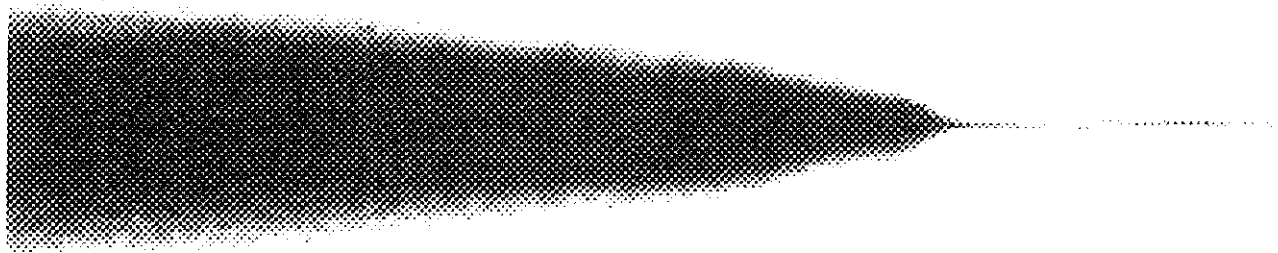


Fig. 8e Nearly-conical vortex breakdown for $Re \approx 100,000$ and $\Omega \approx 0.61$

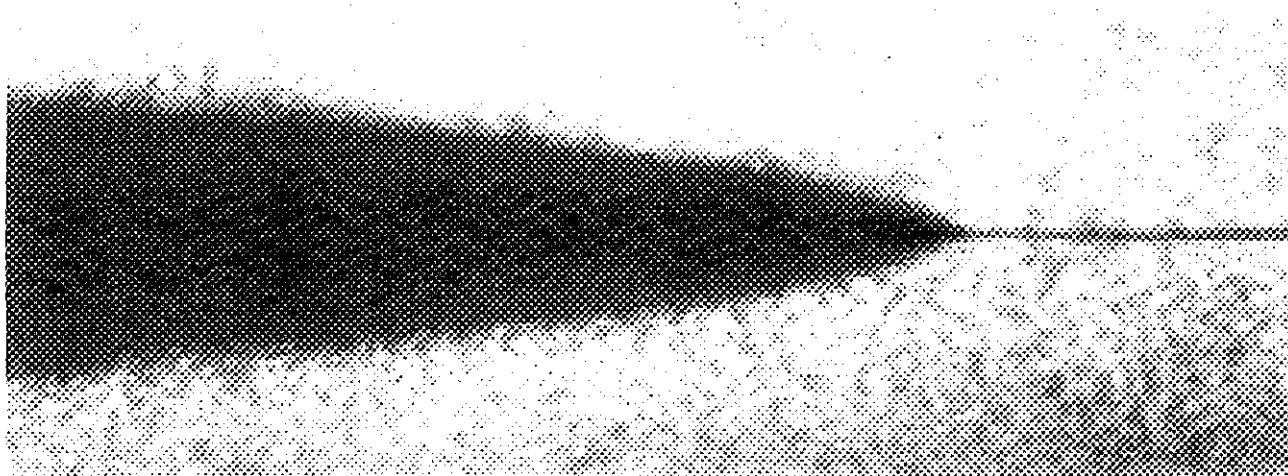


Fig. 8f Nearly-conical vortex breakdown for $Re \approx 150,000$ and $\Omega \approx 0.55$



Fig. 8g Conical type of vortex breakdown for $Re \approx 200,000$ and $\Omega \approx 0.50$